Style Definition: Style1: Font: Bold, Centered

Style Definition: Title

AGRICULTURE RECONSTRUCTION AND DEVELOPMENT PROGRAM FOR IRAQ

STRATEGY FOR WATER AND LAND RESOURCES IN IRAQ
Phase 1 Project Completion Report
Volume 4 – Annex 18 – Reservoir Optimization Model Pilot Application

October 2006

This publication was produced for review by the United States Agency for International Development. It was prepared by author? for Development Alternatives, Inc.

Development Alternatives, Inc

STRATEGY FOR WATER AND LAND RESOURCES IN IRAQ
Phase 1 Project Completion Report

Volume 4 – Annex 18 – Reservoir Optimization Model Pilot Application

Executive Summary

The US Army Corps of Engineers' Hydrologic Engineering Center (HEC) has developed a prescriptive reservoir optimization model (PRM) called HEC-ResPRM. ResPRM is an optimization modeling software package for use with multi-purpose multi-reservoir systems. Using economic-based or generic preference penalty functions and period-of-record or synthetic flows, ResPRM minimizes the penalties at all reservoirs, stream reaches, and diversions in order to identify the optimal reservoir operation solution for the entire system. This software allows modelers to determine the optimal system performance and trade-offs between different interests. ResPRM shares the same basic interface with ResSim, the HEC reservoir simulation software. ResSim is currently being used for a large modeling effort for Iraq's water resources. The first building block for a model in either of these software packages is the watershed setup, or representation of the physical system. This watershed setup, once built in one software package can be opened and used in the other, easing the translation of a model between ResSim and ResPRM. Eventually, the two will reside in a single, multifunctional software package with both building off the same reservoir modeling system.

In conjunction with ResSim training, the Iraq Ministry of Water Resources (MoWR) was introduced to the ResPRM. Due to the Ministry's strong interest in this modeling software, HEC proposed to work with the MoWR and HSC to develop a pilot HEC-ResPRM model for a watershed within Iraq. The pilot study is intended to demonstrate the potential for using this software to optimize operations for reservoir systems in Iraq. The study offers an idea of the time and work investment needed to develop such a model and covers the general approach and data needs, as well.

The Diyala River Basin was selected for the development of the Iraq HEC-ResPRM pilot model. This particular system was chosen mainly because it met the criteria for a good pilot model – small, manageable, ease of model construction, prior system modeling. The Diyala system could be broken down into a fairly simple structure, with two reservoirs, one main inflow, and three diversions. Because a ResSim model of an area including the Diyala had already been built, the basic network layout and much data had already been compiled. Using this information along with some additional research, a pilot ResPRM model was constructed for the Diyala River Basin. This model is not intended to perfectly represent existing conditions; rather, it demonstrates the approach to development and use of a ResPRM model, using reasonable estimates of data and operational objectives for the watershed. Further model refinement can result in a more real-life applicable model, but is outside the scope of this pilot project and will be left to the discretion of MoWR.

This report documents the effort involved in developing a ResPRM optimization model for a reservoir system in Iraq. It includes a summary of the setup, study data, assumptions, approach, and an introduction to the review of results and sensitivity runs.

Finally, it describes ways to expand the use of the software and future possibilities. In conjunction with HEC-ResSim training, MoWR Staff may receive basic, minimal advice in the use and development of their own HEC-ResPRM models. If the implementation is deemed successful, further HEC-ResPRM modeling can be recommended.

1 Introduction to HEC-ResPRM

Optimization is the approach to solving problems that seeks the best solution by maximizing a set of goals in the form of an objective function, subject to specified constraints. Reservoir management can be improved by using optimization modeling in conjunction with the time-honored empirical approach. Optimization modeling can be used to identify the optimal long-term operational strategy for a system of reservoirs. The information obtained from an optimization model can then be used to adjust and improve upon rules developed over years of experience and observation.

The US Army Corps of Engineers' Hydrologic Engineering Center (HEC) has developed the prescriptive reservoir optimization modeling package, HEC-ResPRM.. This software takes HEC's original reservoir optimization software, PRM, and adds a Java-based GUI. PRM is a prescriptive model that addresses a reservoir system operation problem as one of optimal long-term allocation of available water. The GUI was implemented as part of the "Res", or Reservoir Evaluation System, developed for HEC's NextGen software project. This GUI allows users to more easily visualize the physical/spatial structure of the system and its implementation in the model. It also eases the process of populating the model with data. Generally, this makes PRM more accessible and easy to understand.

PRM stands for Prescriptive Reservoir Model. "Prescriptive" indicates that a specific solution is *prescribed* by the model itself, as opposed to "descriptive," which analyzes past conditions to offer a general description of the system. PRM can be used for multi-reservoir multi-objective problems. It currently uses a one month time step, but future versions will allow half-month steps. It is a deterministic optimization model for networks of reservoirs, junctions (nodes), reaches, and diversions. In network flow problems, no constraints are used, but upper and lower bounds can be placed on reaches and penalty functions are used in the objective function to coax the solution into the right realm.

There are few software packages available which offer the ability to conduct optimization studies on reservoir systems, as HEC-ResPRM does. The Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado at Boulder has produced the only other widely available optimization software that was designed specifically for use with reservoirs. This software is Riverware, which does simulation and optimization modeling. Otherwise, there are some software packages that could be used for reservoir optimization, should the modelers have a high degree of knowledge and understanding of optimization. These generalized optimization software packages, such as GAMS, Lingo, and AMPL, could be used to a skilled modeler to develop reservoir optimization models. HEC-ResPRM is, however, the only available optimization software that has been designed for use with reservoir, and is, in addition, entirely free. This is a groundbreaking development for water resources operations and research.

The model identifies the allocation of water that maximizes total benefits by minimizing the costs associated with poor performance for all defined system purposes. Performance is measured with user-provided penalty functions based on flow, storage, or both. To determine the optimal water allocation, ResPRM represents the physical system as a network, and the operating problem is formulated as a minimum-cost network flow problem. The objective function of this network problem is the sum of piecewise-linear approximations of the penalty functions. An off-the-shelf solver is used to determine the optimal allocation of water within the system. The results of the solver are processed to report and display reservoir releases, storage volumes, channel flows, and other pertinent variables. The Res implementation also allows users to produce important graphs directly from the GUI.

The HEC-PRM users' manual describes the optimization technique like this:

> HECPRM considers the reservoir operation planning problem as a problem of optimal allocation of available water. The solution procedure for this water allocation problem is as follows:
>
> 1) Represent the physical system as a network;
> 2) Formulate the allocation problem as a minimum-cost network flow problem;
> 3) Develop an objective function that represents desirable operation;
> 4) Solve the network problem with an off-the-shelf solver; and
> 5) Process the network results to define, in convenient terms, system operation.

2 Study Background

The Iraq Ministry of Water Resources (MoWR) were introduced to HEC-ResPRM in conjunction with lessons on HEC's reservoir simulation modeling software. Having seen this software, a keen interest in the potential of using this reservoir optimization software in Iraq was expressed. Therefore, an HEC-ResPRM pilot model was planned. The Diyala River Basin was selected for the development of the Iraq HEC-ResPRM pilot model. The Diyala headwaters originate in Iran, but this study only considers the features within Iraq and models upstream elements as a single inflow to the uppermost reservoir. The Iraqi Diyala system includes two power-generating reservoirs, the Derbendi Khan and Hemrin Reservoirs, and three major irrigation diversions, the Middle

Diyala, Mushtarak (Combined-Head Reach), and Al Khalis diversions. Final outflow from the watershed flows to the Tigris at a junction just south of Baghdad. Originally, the Diyala watershed setup previously developed using HEC-ResSim, HEC's reservoir simulation modeling software, was planned to be imported into the HEC-ResPRM model. However, the modelers' interpretations of some elements varied between ResSim and ResPRM. Therefore, for the purpose of the HEC-ResPRM model, the Diyala watershed setup previously developed for use in HEC-ResSim was adapted with slight but necessary modifications.

An executable pilot model was developed for the Diyala River Basin. Three main objectives of reservoir management were identified and prioritized as follows: irrigation supply, hydropower generation, and flood control. Penalty functions were developed for diversions and operations, based on these priorities. These are used to penalize allocation of water that is not within the desired bounds. For example, water releases that do not meet the demand for irrigation are penalized at a decreasing rate, from a maximum penalty when demand is not met at all, until a penalty of zero is reached when releases fully meet demand. The model allocates water in such a way as to achieve the minimum sum of resulting penalties for all interests. The penalty functions developed for this pilot model strive to fully meet irrigation demand, supply at least 80% of the hydropower generation capacity, and minimize flooding, as well as provide minimum in-stream flows at the Diyala-Tigris junction.

Monthly model inflows were provided based on historical records of inflows to the Derbendi Khan Reservoir. Middle Diyala inflows were neglected due to the lack of adequate data. Other relevant data collected were minimum hydropower generation pools, stage-storage-surface area curves, outlet structure capacities, and irrigation demand. These were obtained from various sources, including the reports from the USACE Portland District work in Iraq, the Harza 1963 report, and other information supplied by the Center for Integrated Water Resources Management of the MoWR. For future studies, additional useful data include flood damage potential, channel capacities, crop types and value of irrigation supply, and hydropower demand and value.

3 Building the ResPRM Diyala Pilot

A network flow model consists of flow paths called arcs connected by nodes. Penalty functions are used to express the model objectives. To build the ResPRM network flow model, the user begins by laying out the physical paths and nodes, then adds the physical characteristics of the layout, then adds penalty functions.

The structure of the ResPRM model is much like that of ResSim. The user interface consists of three separate modules. In order to build a model, the user begins by creating a watershed setup, which is the same as the ResSim watershed setup. This is basically a background map of the watershed with basic stream alignments and project elements such as reservoirs, diversions, and nodes. A configuration of project elements is created in this module. Next, a network configuration is developed. (A screenshot of the network configuration can be seen in Figure 1.) Using the watershed setup as a base, routing reaches are added to the model. Then the physical properties are added. Penalty functions are defined in the network module. Alternatives are then built, by specifying combinations of penalty functions, input data, and various details for the simulations. Finally, simulations, which will be the model runs, are made for the alternatives in the simulation module. Results can also be viewed in this module.

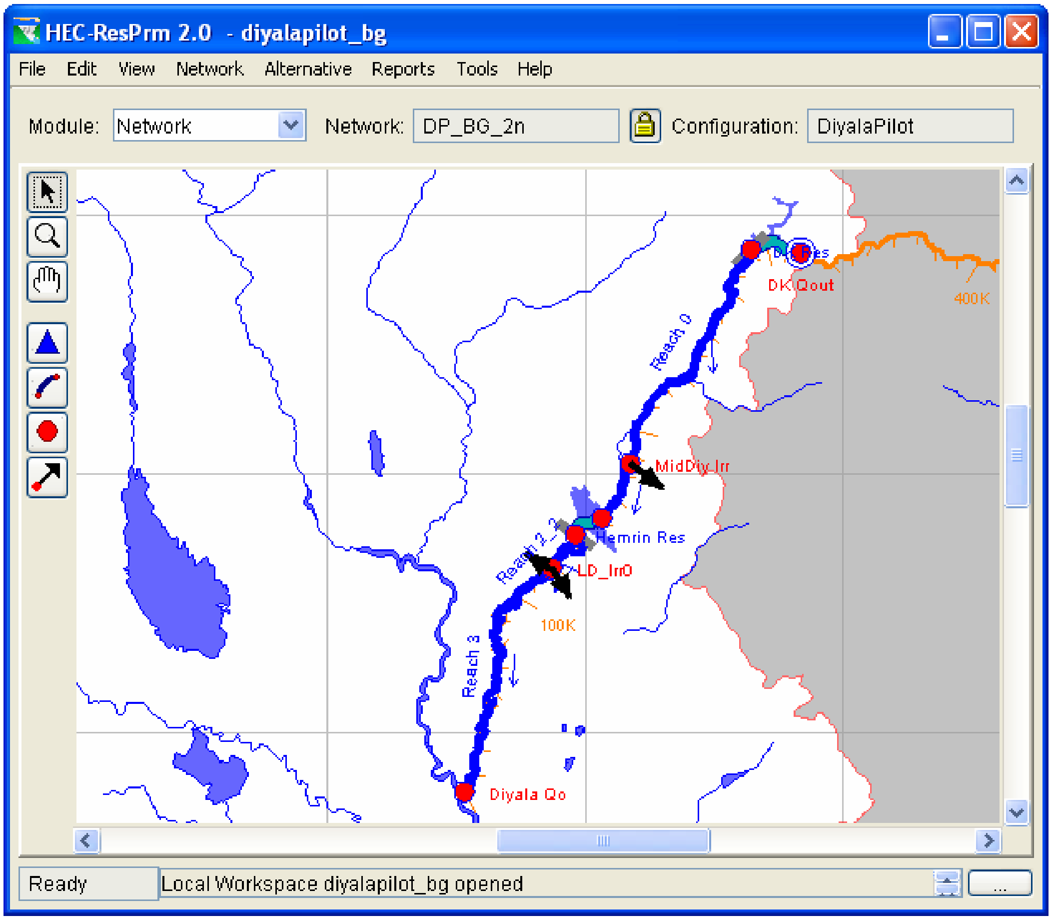


Figure 1 This screenshot of the Diyala Pilot network layout shows the model's graphical representation of the physical system.

The following section describes the process of developing the pilot model. It starts with the data collection and assumptions, and goes on to describe the layout of the model, determination of constraints and derivation of penalty functions, all of which contributed to the construction of the alternatives. Detailed instructions for duplicating the model setup in ResPRM can be found in Appendix A.

3.1 Data and Assumptions

The data used to build the Diyala Pilot model was obtained from various reports and sources. MoWR documents and Army Corps reports were used, particularly the Iraqi Dam Assessment Report (U.S. Army Corps of Engineers, 2003) and the MoWRDam Assessment fact sheets There is significantly conflicting data available through these reports, fact sheets, the Diyala ResSim model, and other sources. In order to deal with these discrepancies, values were arbitrarily chosen to represent data in the pilot model. These values, of course, can be adjusted to better represent present conditions, should a more accurate model be desired. So while most data entered into the model are easily changeable, it is useful to note why they were selected and even the impetus for setting up the ResPRM pilot model as it is. This report section is used to document the decision-making process, or at least the values selected for the ResPRM Pilot Model development.

Data required for the Diyala Pilot Study includes the following:

- spillway capacity
- Probable Maximum Flood*
- current flood reservations (rule curve)
- stream/channel capacity*
- storage-flood damage relationships*
- flow-flood damage relationships*
- monthly irrigation water demand
    - type of crops (annual/perennial)*
    - irrigation-profit relationships*
- reservoir capacities
- inflow data at all points*
- hydropower capacity, demand, generation*

Asterisked entries are those for which well-defined data was unavailable, unclear, or debated.

Tables 1-6 present the data used to populate the pilot model. Most data was obtained from the Iraqi Dam Assessment Report (2003), as this was the most recent and complete information available. Irrigation data was provided by MoWR. Other data was estimated due to insubstantial data. These are noted with asterisks. The values shown in the following series of tables (Tables 1 – 6) were used to develop the Diayala ResPRM model.

TABLE 1 DERBENDI KHAN RESERVOIR STAGE AND STORAGE				
	STORAGE (M^3)	**STORAGE (KAF)**	**STAGE (M)**	**STAGE (FT)**
max level	3,800,000,000	3,080.71	493.5	1,619.09
norm op level	3,000,000,000	2,432.14	485	1,591.21
HP generation min level	470,000,000	381.04	434	1,423.88

Table 2 Derbendi Khan Reservoir Outflows		
	FLOW (M^3/S)	FLOW (AVG KAF/MON)
turbines	330	703.56
irrigation	3,175	6,769.14
est low flood**	7,305	15,574.36
est high flood**	11,105	23,676.01
spillway	11,400	24,304.95
TOTAL**	14,905	31,777.66

Table 3 Hemrin Reservoir Stage and Storage				
	STORAGE (M^3)	STORAGE (KAF)	STAGE (M)	STAGE (FT)
max level	3,760,000,000	3,048.28	107.5	352.69
norm op level	2,400,000,000	1,945.71	104	341.21
HP generation min level	100,000,000	81.07	89	291.99

Table 4 Hemrin Reservoir Outflows		
	FLOW (M^3/S)	FLOW (AVG KAF/MON)
turbines	200	426.40
irrigation	250	533.00
est low flood**	1,950	4,157.43
est high flood**	3,450	7,355.45
spillway	4,500	9,594.06

TOTAL	4,950	10,553.47

Table 5 Irrigation Diversions		
	FLOW (M^3/S)	**FLOW (AVG AF/MON)**
Middle Diyala	31.25	66.63
CHR	138.75	295.82
Al Khalis	75	159.90

Table 6 Diyala-Tigris Junction		
	FLOW (M^3/S)	**FLOW (AVG AF/MON)**
min Q_{out}	13	27.72
ideal Q_{out}	65	138.58
max Q_{out}	3,712.5	7,915.10
est low flood**	1,462.5	3,118.07
est high flood**	2,587.5	5,516.59

Conversions to British units were necessary for use of the current version of ResPRM, though future versions will allow SI units. Monthly inflow values were easily converted from cms to AF/mo. Target flows, minimum or maximums that are invariable over all timesteps had to be estimated with average monthly values. In order to convert cubic meters per second to acre-feet per month, an average number of days per month was used, such that every month is assumed to have the same (average) flow value, despite the fact that the flow, in reality, would vary with the days in the month.

Minimum and maximum reservoir levels were required, along with outlet and channel capacities. These were obtained from the Iraqi Dam Assessment Report. The stage-storage-area relationships were obtained from the HEC ResSim model. It should be noted that the stage-storage-area curves provided by MoWR were inconsistent with the

Iraqi Dam Assessment, in that maximum and dead storage capacities did not agree. This inconsistency was disregarded for the purposes of the pilot model.

Two levels of flooding were used in penalty function development. A low flood was assumed to be the total of maximum releases possible through the irrigation outlets and turbines, plus one third of the flood spillway capacity. A high flood was assumed to be the total of maximum releases possible through the irrigation outlets and turbines, plus two thirds of the flood spillway capacity. For the downstream Diyala reach, flood levels were assumed to be 75% of flood releases from Hemrin.

3.2 Assigning Constraints

Optimization with network flow models does not allow for the use of standard constraints associated with most linear programming. Instead, its strict network setup has a more specific form, such that optimization relies primarily on the objective function subject to specific flow paths. Capacities, consisting of the upper and lower bounds on a storage link (reservoir) or flow link (channel), can be set, but otherwise, there can be no constraints in the network flow formulation. These capacity constraints must be defined accurately without being too binding. When a constraint is too binding, it plays too great a role in determining operations. Ideally, the only constraints defined will be those absolutely necessary. Any non-binding constraints can instead be modeled using penalty curves. This helps to avoid non-feasibility issues and gives the user better insight on the extent of the impact or importance of certain rules and constraints. Future versions of the model will include the option to add side constraints, explicit, non-capacity constraints.

The Diyala Pilot model required minimum and maximum storages and releases at the reservoirs. Diversions were assigned minimum and maximum flow constraints. Channels can also be assigned constraints, but this information was not known. The exact values assigned can be seen in Tables 1 - 6. The following paragraphs describe the constraints used in the pilot model.

Maximum reservoir storage was assigned and the minimum storage was defined at the level of dead storage. (Figure 2 shows the HEC-ResPRM reservoir editor and the storage constraints for Hemrin Reservoir.) Although it would be more realistic to relate reservoir release to storage, a network flow model cannot model such complex relationships, so, minimum reservoir release was assigned to be zero, and maximum release was the sum of total possible release through hydropower, irrigation, and spillway outlets. Minimum and maximum flow constraints can be assigned to reaches, but, with the exception of the reach that releases to the Tigris, these were not defined in the Diyala Pilot. Streamflow capacities were unknown, and in such a simple model, this will be somewhat constrained by the restrictions on reservoir releases. Channel capacities were assumed to be infinite or at least able to handle the highest output from the reservoir with the exception of the channel that flows into the Tigris.   This channel was assumed to have minimum and maximum flows and flood penalties.

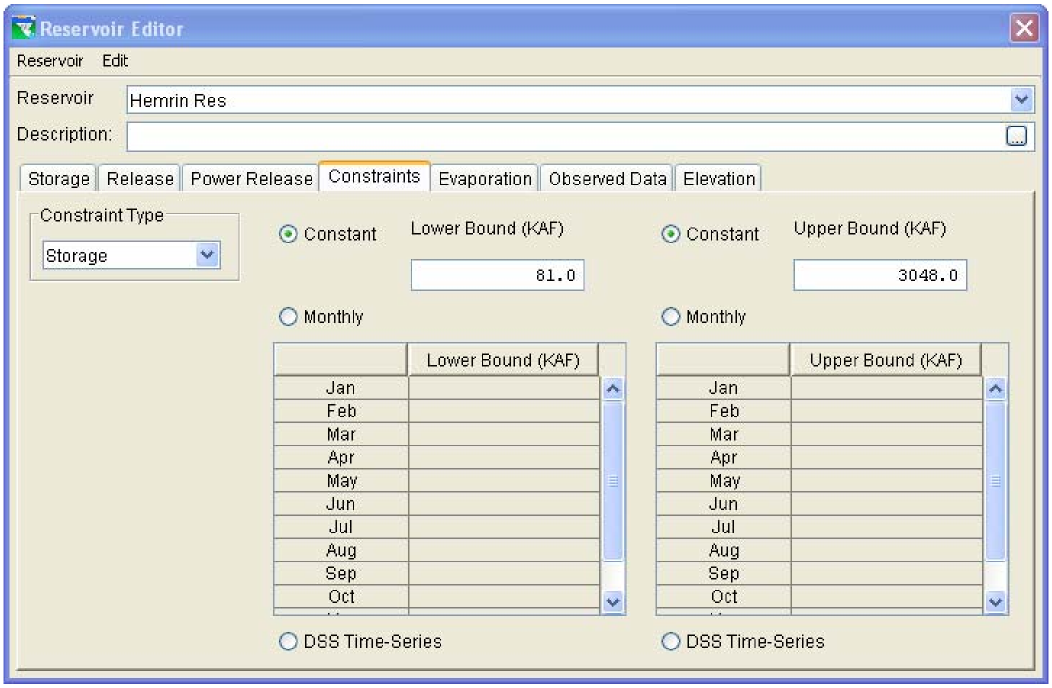


Figure 2 Storage constraints at Hemrin reservoir are constant over time, although, as seen in this screenshot, they can vary monthly or be entered as timeseries data.

Diversions have minimum and maximum flow constraints. Minimums were assigned as zero, and maximums were assigned as 25% greater than the maximum monthly irrigation demand, except in the case of Al Khalis, for which a design maximum was provided by MoWR. The flow through the final reach going to the Diyala-Tigris junction was also marked with minimum and maximum capacities. These capacities were based on matching outflow from the Hemrin Reservoir, but a side constraint would be needed to restrict flows to a certain percentage of the Hemrin release. In order to select a single constraint value, period-of-record average Hemrin releases were used. The minimum and maximum flows were assigned as 10% and 75%, respectively, of the average outflow from Hemrin reservoir.

3.3 Penalty Function Formulation

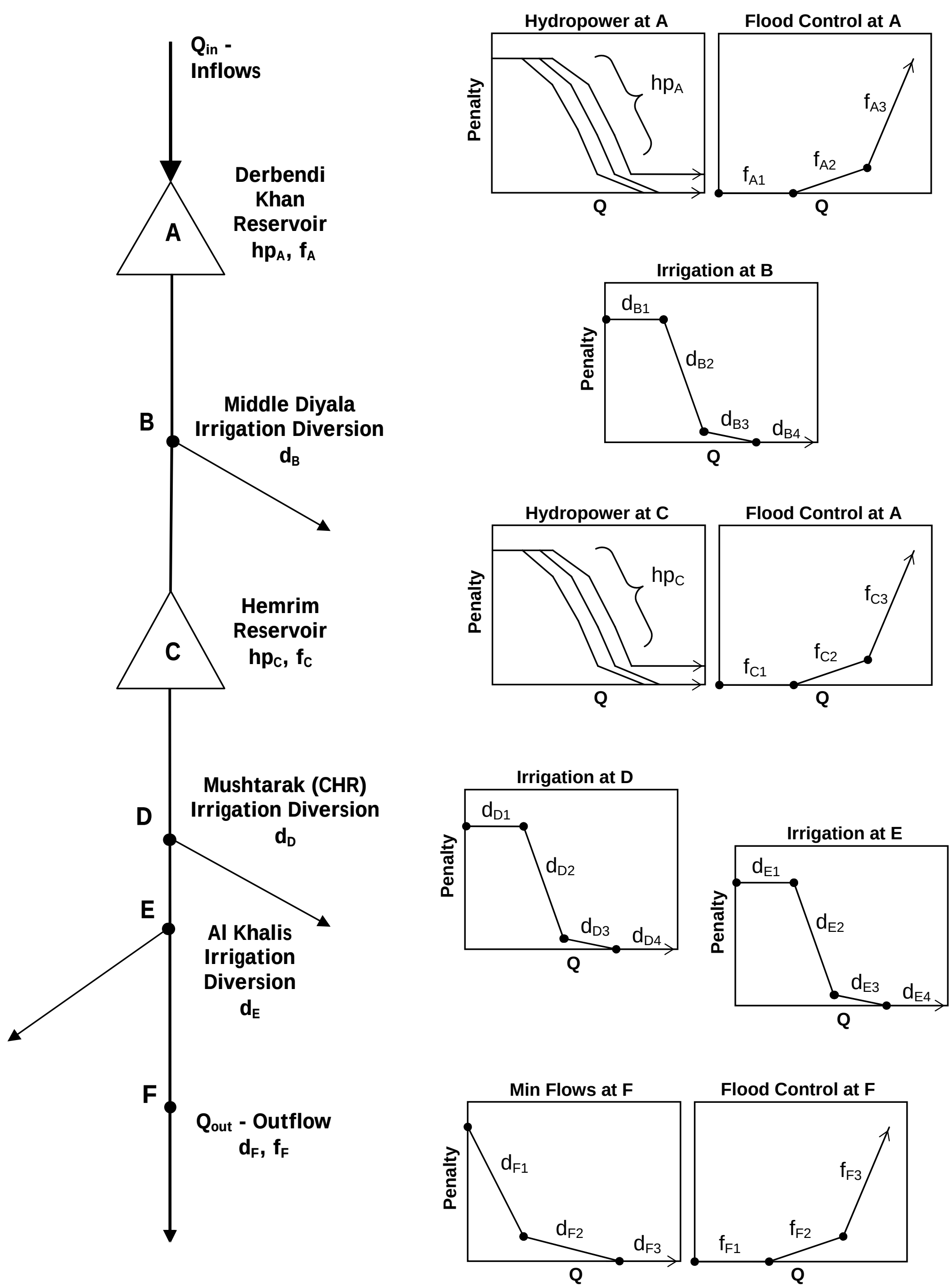
In order to formulate a minimum cost linear network flow problem, penalty functions are needed The objective function for the PRM model is the composite of all penalties at all locations. This function is minimized for all timesteps and elements at once in order to find the optimal solution, or the best allocation of water for the entire system. This allows the modeler to play with the balances and tradeoffs between meeting various demands and avoiding flood risks.

Penalties can be economically based, or can use other measures to account for objectives that can not be quantified in monetary units. There are multiple ways to develop penalty functions. If financial data were available it could be used to develop straightforward penalty functions based on the marginal cost or benefit of a unit of water. However, the data available for the Diyala pilot does not include any monetary information. Penalty functions were based strictly on assumed priority of the various interests in the watershed.

The important features of a penalty function are its shape and magnitude. Penalty functions describe the relationship between the decision variable (flow or storage) and the unit cost to the system. The unit cost may be a constant or a changing value based on the decision variable. Typically they vary to the extent that penalty functions are usually made from piecewise linear penalty functions. Negative penalties can be used to indicate positive impacts of a unit of water. When developing non-economic penalty functions, the shape and magnitude of the functions are somewhat arbitrary, in comparison to the direct use of monetary data. The shape of the penalty function determines the internal relationship within that particular objective. the magnitude determines the relationship between that objective and the others. Prioritization is based strictly on the unit cost, or slope of the penalty function compared to that of others.

Modelers developing the shape of the penalty functions must be concerned with convexivity. A convex penalty function is one for which the unit cost is always increasing as the decision variable increases. Should the penalty decrease, the LP solver used for network flow problems will be unable to find a solution. When nonconvex penalty functions are defined, the PRM solver can be set to use an optimization algorithm that can handle nonconvexivity, however, solution time is longer and a global solution cannot be guaranteed. Therefore, the user has the decision to either simplify the model such that all penalty functions are convex, or accept the risk of not getting a global solution, and possibly repeating model runs with different initial values to improve the chances of finding a global optimum. For the Diyala pilot, nonconvex penalty functions were used to describe irrigation and hydropower objectives. The restricted basis entry algorithm was used to solve the model.

In order to develop penalty functions, it was first necessary to determine the existing priorities and relationships between various demands and needs on the system. It was decided that the interests to be modeled in the pilot would be flow-based flood control, irrigation supply, and hydropower. Beginning upstream, and working down the system, the locations and types of penalty functions were identified. The methodology used was to first determine the general shape of each penalty function based on the relationship between flow (or storage) and cost. Having determined the general shape, the next step was to determine the magnitude of the associated slopes, such that existing relative priorities are represented. This step is described in detail in Appendix B. Figure 3 depicts the model layout and shape of the penalty functions associated with each part of the model. The process of determining the penalty function shapes is described in this section.



Qin - Inflows
Derbendi Khan Reservoir
hpA, fA
A
B
Middle Diyala Irrigation Diversion
dB
Hemrim Reservoir
hpC, fC
C
D
Mushtarak (CHR) Irrigation Diversion
dD
E
Al Khalis Irrigation Diversion
dE
F
Qout - Outflow
dF, fF
Hydropower at A
hpA
Flood Control at A
fA1
fA2
fA3
Irrigation at B
dB1
dB2
dB3
dB4
Hydropower at C
hpC
Flood Control at A
fC1
fC2
fC3
Irrigation at D
dD1
dD2
dD3
dD4
Irrigation at E
dE1
dE2
dE3
dE4
Min Flows at F
dF1
dF2
dF3
Flood Control at F
fF1
fF2
fF3
Penalty
Q

Figure 3. Diyala system layout and corresponding penalty curves

General penalty function formulation

The potential flow paths for a unit of water in the Diyala system were determined. Each alternative flow path must be considered in order to ensure that penalties are selected that enforce the desired priority structure. Letters refer to the labels shows in Figure 3.

Potential flow paths for a unit of water:

starting at Derbendi Khan (A)

A (storage)
A → B (sink)
A → C (storage)
A → C → D (sink)
A → C → E (sink)
A → C → F (sink)

starting from storage at Hemrin (C)

C (storage)
C → D (sink)
C → E (sink)
C → F (sink)

Figure 4 shows the shapes of the penalty curves used in this model. It labels each piece of the piecewise linear functions with its unit penalty cost. This value does not represent the value of the penalty, rather, it represents the slope of the curve, or the marginal cost of water at that flow level. It is this value that is of consequence to linear optimization and how optimal is determined.

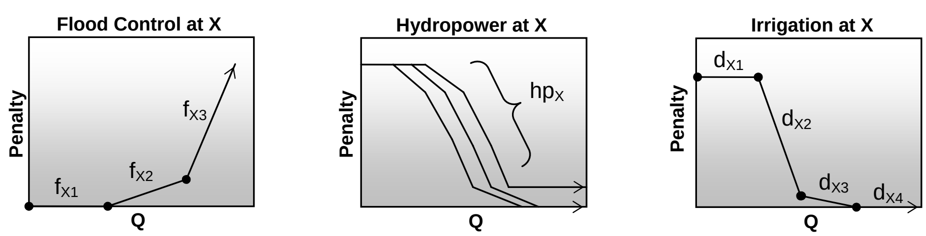


Figure 4 These generic penalty functions demonstrate the way penalties can be set for various interests in the system.

Hydropower

Hydropower generation is a nonlinear function of both net head and release. In order to reasonably represent this relationship, PRM allows users to define multiple penalty functions, each based on a different storage level. It then uses an iterative process to select the release and corresponding storage level for minimum penalty. This is, of course, an approximation of the actual complex conditions of power generation. All reservoir outlets in ResPRM are represented as one combined outlet. Users cannot divide reservoir releases into those that go through various gates or culverts, instead, penalty functions must be defined solely on TOTAL reservoir releases, with no distinction between actual route taken out of reservoir. Therefore, any time water is being released from the reservoir, it is assumed to be generating power.

Penalty functions for hydropower at Derbendi Khan and Hemrin Reservoirs were based on the turbine performance/efficiency curves. Penalty curves are entered into the model as penalty per unit of flow. Multiple curves can be used, each based on performance at a different reservoir storage. Given limited information on the hydropower plants, only one penalty function was used at each reservoir, rather than a spectrum of different penalty functions at different storages. A series of flows were defined and a net head assumed. The power produced under these conditions was estimated with the help of the performance curve charts. Penalties were assigned based on the percent of maximum power resulting at each flow level.

These penalty curves can be significantly improved with information related to relationships between reservoir storage, releases, and power generated. For example, the degree to which tailwater might change with flow was unknown. Instead, it was assumed that as long as flows were greater than the minimum needed to produce at least 80% of maximum power, that enough power was being generated, and no penalty was incurred at any release levels higher than that. Unit penalties above 80% capacity and at no power generated are 0. Unit penalties between the two are based on expected power generation. This is roughly approximated and not represented in detail in Figure 3.

Flood Control

The Diyala River hydraulic structures operate to mitigate flood conditions in this tributary basin to the Tigris as well as along the river reaches below the Tigris-Diyala confluence. It was assumed that the first priority on this basin is to minimize the number of extreme floods. Flood penalties were placed at three locations on the basin, Derbendi Khan, Hemrin, and Diyala outlet releases. In the initial model trial, no flood penalties were put on reservoir storage. Later alternatives added storage flood penalties because reservoir levels were consistently too high.

Development of flood control penalties involved estimating low and high flood threshold levels. It was assumed that no damage would occur until reaching the low flood threshold, beyond which damage was assumed to increase with increasing flow until reaching the high flood threshold, at which the damage rate-of-increase would be greater. Because channel capacities were unavailable, estimates were based on reservoir outlet capacities. For Derbendi Khan and Hemrin Reservoirs, ResSim model operations call for maximum outflows of 3,000 and 2,000 m^3/s, though their capacities are actually in the 10,000's. Therefore, it was assumed that the ResSim maximum is just an operational preference, rather than a restriction based on actual flood damage. The downstream infrastructure and development is unknown, however this information could be used later to specify more accurate levels at which flood damage would occur, helping to build better penalty functions. For the pilot model, however, low flood thresholds were assumed to be equal to the maximum capacity of the hydropower and irrigation outlets plus one third the maximum spillway capacity. A high flood threshold was assumed to be the same as low flood, except two thirds the maximum spillway capacity instead of one third.

No penalties were assumed for normal flows. Above normal flows incur a slight penalty and high flows incur a rapidly increasing penalty. Unit penalty relationships are as follows:

$f_{x1} < f_{x2} < f_{x3}$

$f_{x1} = 0$,

which holds true at Derbendi Khan, Hemrin, and the outflow, where x = A, C, and F, respectively.

Irrigation Diversions

Irrigation penalty curves were constructed to reflect the percent of irrigation demand met. Anything between zero and 20% of demand is fully penalized, under the assumption that crops will die at any irrigation level below 20% of demand and the marginal value of water at this level is zero. No penalty is incurred for meeting 100% of demand. A small unit penalty is incurred for meeting between 90% up to 100% of the demand. Between 20% and 90%, the unit cost of not meeting demand is higher. The unit cost relationships, therefore, relate as such:

$d_{x1} = 0$
$d_{x4} = 0$
$d_{x1} > d_{x2} > d_{x3}$

Thus, d_{x2} and d_{x3} are negative unit penalties. (Penalty decreases as flow increases.)

In-stream Minimum Flows

In order to maintain water quality, certain minimum flows must be maintained. This is primarily a concern in the reach downstream of the Lower Diyala irrigation diversions, where the Diyala joins the Tigris River. According to recent discharge records, minimum instream flows downstream of the Diyala Weir range from 5 to 20 cms. For the purposes of this pilot model, criteria was set to avoid any flows lower than 10% of the irrigation demands.

Total irrigation demand for the Mushtarak and Al Khalis irrigation diversions were determined based on average demands. A minimum of 10% of the average monthly value was selected as a breakpoint for the penalty curve. A second breakpoint was implemented at 20%. Unit penalties in this flow regime are less. Flows above this level incur no minimum flow penalty and have a marginal penalty cost of zero.

$q_{F3} = 0$
$-q_{F1} > -q_{F2} > q_{F3}$

Diyala Pilot Penalty Function Examples

To demonstrate the appearance of penalty editor in ResPRM, a screenshot of the model, showing the entry of a penalty function into HEC-ResPRM is shown in Figure 5. The selected model element is shown at the top. Below are a series of tabs that allow the modeler to input different types of data – penalty functions for storages or releases, constraints, stage-storage data, etc. On the left hand side, the penalty functions are shown and data is entered in the large table. It can be entered based on month or for the full year. Finally, there is a weight factor that could be adjusted to change the effect of a penalty relative to others in the model, and a plot of the penalty that has been entered.
Figures 6 – 10 show examples of actual penalty functions used in the Diyala pilot model. These examples show how the penalty functions look in the user interface.

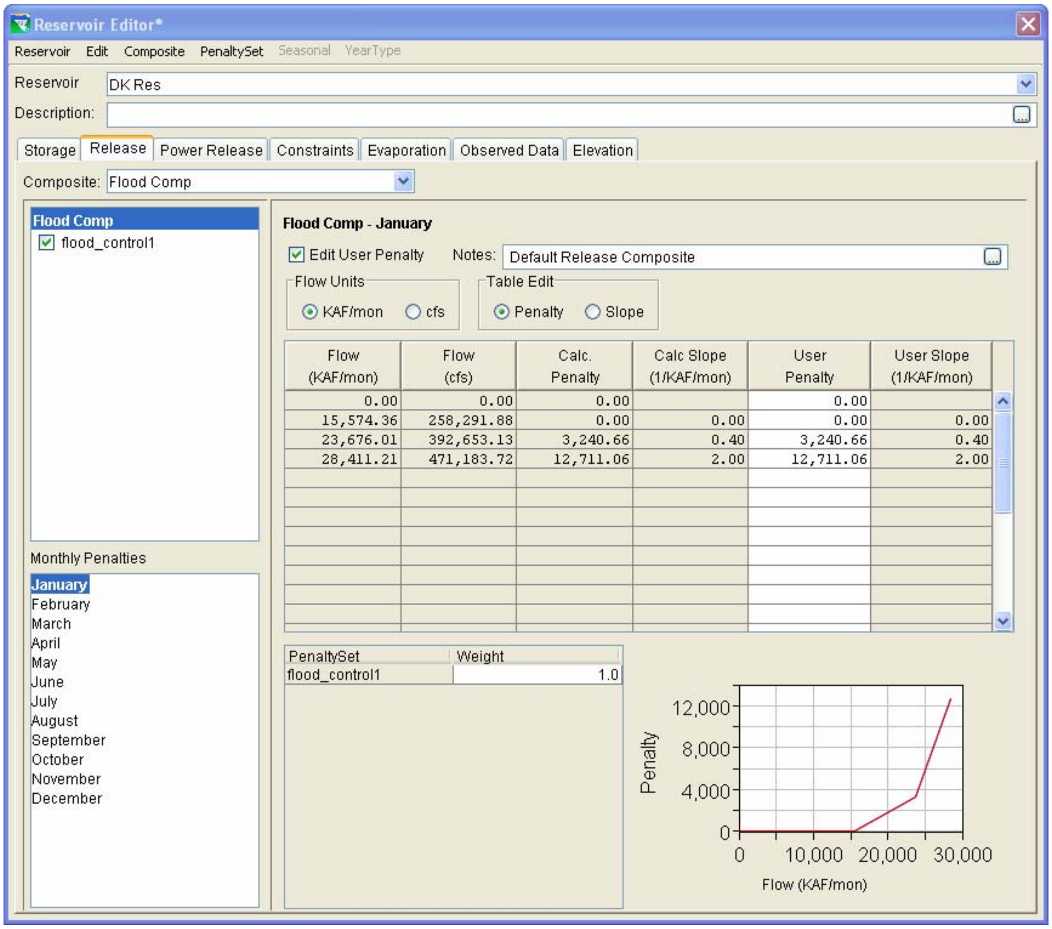


Figure 5 This screenshot of the Reservoir Editor shows the penalty function defined for flood control at Derbendi Khan Reservoir.

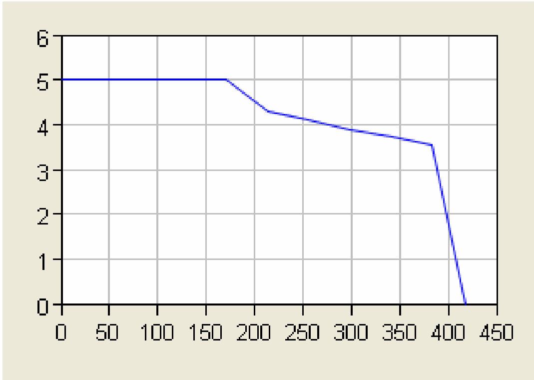


Figure 6 This plot shows the hydropower penalty functions at Hemrin Reservoir. The y-axis is the unitless penalty and the x-axis is the flow in kAF/month. Because there is only one curve, the penalty is the same at all storage levels; otherwise a different curve would be defined for each storage level.

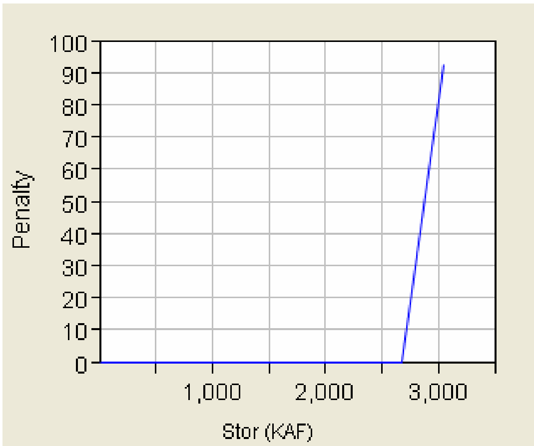


Figure 7 This plot shows the penalities against flood-level storages at Hemrin Reservoir. There is no penalty until the storage level is greater than 67% of the pool between normal operating level and the maximum level, 2680 kAF, then penalty increases rapidly.

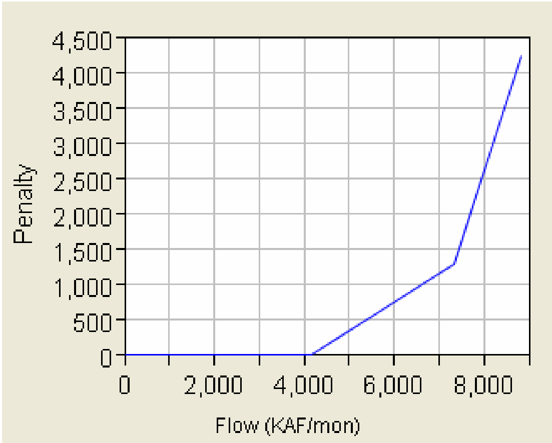


Figure 8 This plot shows the penalties against flood releases at Hemrin Reservoir.

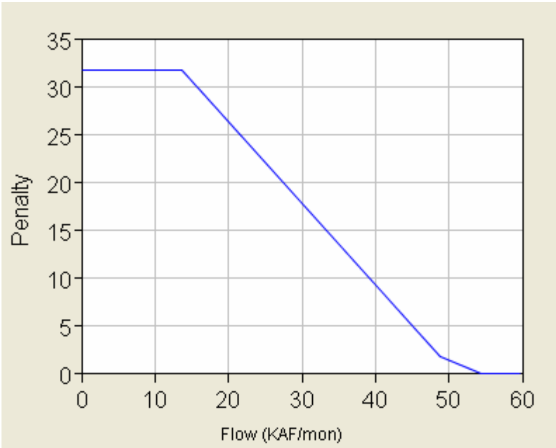


Figure 9 This plot shows the January penalty curve for irrigation at the Al Khalis diversion. Penalty is maximum at 20% of the demand, below which, irrigation water has no value, as it is assumed the crops are dead.

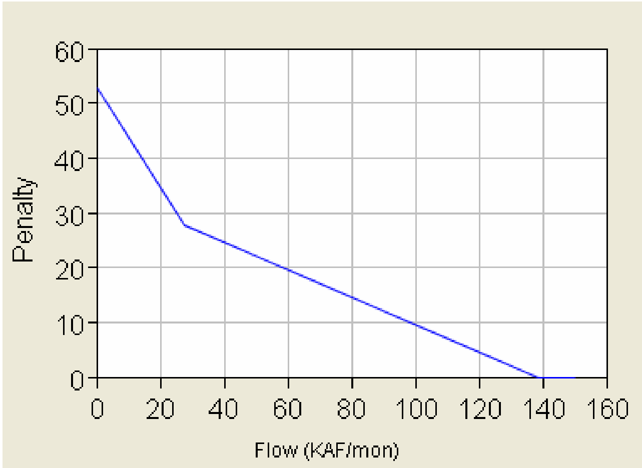


Figure 10 This plot shows the minimum flow penalty at the Diyala stream reach that flows into the Tigris. Flows below 10% of the demand are penalized more than those lower.

Priority Ranking

In order to assign penalty curves to various interests in a system, it is important that the penalty curves will correctly prioritize the competing interests. When interests on a system can all be associated with a cost or benefit in common units, this can be a relatively straightforward task. Penalty curves can be assigned to all the interests in the model based on that common unit, such as dollars or dinars, and the model will automatically prioritize interests based on their monetary cost or benefit. However, the data available on the Diyala river does not include information on the costs of meeting or not meeting certain criteria. Instead, prioritization of all competing interests was arbitrarily determined, the shapes of the penalty curves were determined, and then, the unit penalties had to be selected to reflect that prioritization. These unit penalties were based strictly on that prioritization and are completely independent of any physical properties. The process of determining unit penalties can be found in Appendix B.

3.4 Building Alternatives

Once the watershed system has been laid out, physical properties have been entered, and penalty curves have been added, the model alternatives should be constructed. The alternatives are run in the simulation mode for different time periods. The information that makes up an alternative consists of the configuration, initial and final storage levels for the reservoir, composite penalties, timeseries data sources, and computation options. The computation options include output level and options, scaling and bounds, and whether or not to use restricted basis entry – the approach that allows the solver to handle non-convex penalty functions.

A good approach is to build a basic alternative with the desired features, and then make individual adjustments to that basic alternative for run variations. The most common adjustments are changes in the composite penalty functions. By having several different composite penalty functions at each location, model changes are easier. Other variations in alternatives are different initial and ending values and different penalty weightings.

For the Diyala pilot, a standard model alternative was first built and run. Review of the results led to the construction of several more alternatives. Penalty functions were adjusted on irrigation demands to make them equal at both downstream sites (meaning that CHR will get priority because it is upstream of Al Khalis). In another alternative, flood penalties were added to reservoir storage, because levels seemed to be near the maximum stage far too often. New versions of both of these alternatives adjusted the starting and ending reservoir storage levels. Original starting and ending levels corresponded to “normal operating levels,” but the 50^{th} percentile of the historical record was significantly lower. In total, five alternatives were built for the Diyala pilot.

4 Results and Analysis

The use of ResPRM can improve operating strategies for reservoirs. Analysis of the results will suggest the ideal operating plan or adjustments that can be made to the current operating plan. For example, evaluation of PRM results can help reservoir managers determine if their current operating strategy is too risk averse. It may show that reservoirs need not maintain such deep flood pools based on the overall system priorities. Again, this is a tradeoff between yield and reliability, and depending on the values of the objectives, users can determine how to adjust current rules. However, before an in-depth analysis, it is a good idea to calibrate the model, do some sensitivity runs, and verify the performance of the model.

4.1 Model Verification

Once the model has been setup and run, it should be calibrated to fine-tune the setup, penalty functions, and other features. Sensitivity analysis can be performed by adjusting the demands, turning on and off constraints, changing the shape or magnitude of the penalty curves, and changing initial and ending reservoir levels. A series of calibration can consist of repeated runs can provide successive improvement of the model.

First a standard model run is created. Then, the results can be reviewed to determine where changes in the model might be desirable. The user should identify the locations and times that penalties occur and then determine why they occurred and where the tradeoffs were. If these penalties are not desirable, some of the penalty functions need to be adjusted in order to deter these kinds of infringements. Whether the behavior is reasonable should be determined at all reservoirs, nodes, and other locations. Then, constraints can be adjusted as needed.

In Figures 11 and 12, the results of changing penalty functions can be seen. These runs test the effects of adding a penalty against flood-level reservoir storages. In Figure 11. The upper plot in Figure 12 shows primarily lower storages when the penalties against flood-level storages have been added, as seen in the difference between the blue (no flood storage penalty) and red (with flood storage penalty) lines. Figure 11 shows the degree to which Al Khalis irrigation demands are being met with and without the reservoir flood storage penalties. The red dotted line shows the irrigation demand. The green line shows the modeled flow without the flood storage penalties, whereas the blue line shows flow with the storage penalties. For the run with the flood storage penalties, there are times that irrigation demand is better met, as the upstream reservoirs are penalized for storing too much water, and that water becomes available for irrigation. Figure 13 shows another example of the effects of adapting small changes in the model. This plot shows the differences between reservoir storage over the run period when the start and end storages are set at different levels (assume normal operating conditions). Besides the examples shown here, other types of results from the ResPRM model that are currently or will soon be available include plots of dual cost and penalty incurred in a run.

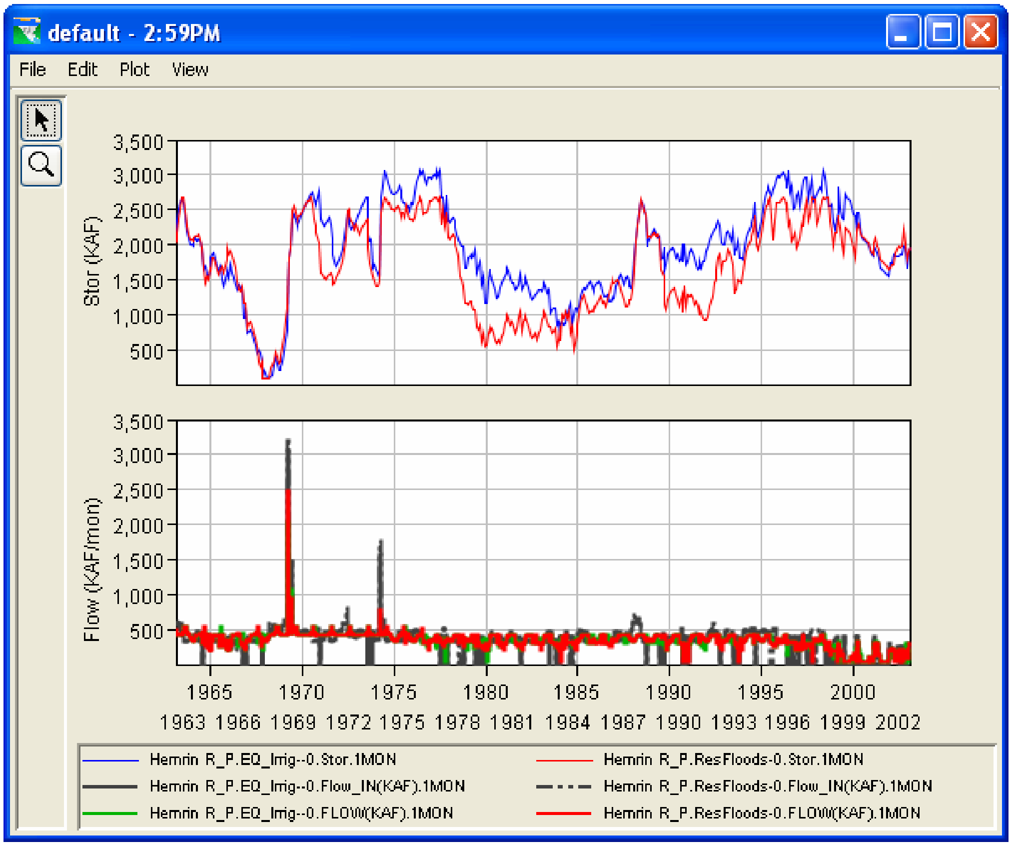


Figure 11 - Hemrin Reservoir storages are lower with a penalty against flood-level storages, as seen in the upper plot

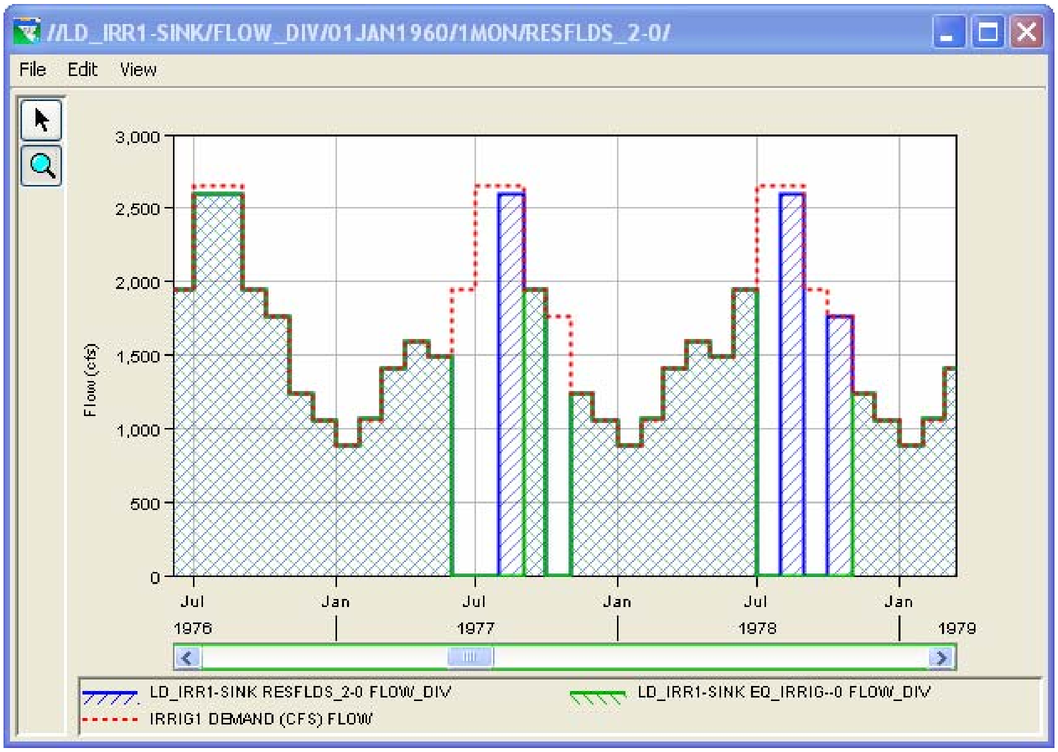


Figure 12 These changes in flows at the Al Khalis Diversion are based on using different penalty functions at the upstream reservoirs.

Figure 13 These plots of Hemrin Reservoir storage and flows show how results vary based on setting different beginning and ending reservoir storages for the model.

The results from the Diyala model runs performed were reviewed to see how well demands and other objectives were met. Adjustments in priorities were made. Beyond the basic model review and calibration, little verification was performed. The pilot model supports a very limited depth of analysis.

Approaches to data analysis can vary. Output can be viewed in the ResPRM GUI, DSS, or exported to another program such as Microsoft Excel. An Excel spreadsheet can be set up to calculate the breakdown of individual penalties that were incurred, make multiple time series graphs of the data, and develop tradeoff curves. Tradeoff curves will help the user to decide on the priority of the different demands on the system. This can be accomplished by doing multiple model runs, each with different weights on different penalty sets.

After the model has been fine-tuned, tests can be run on the performance under various inflow conditions. For example, a series of wet years could be run to see how well the model is able to optimize. Synthetic streamflows can be constructed using the statistical information provided by the available historical record.

Operational guidelines can be inferred using the results of runs for different timeseries. Then the rules can be tested in ResSim, or ResPRM can test rules by making them constraints rather than penalty curves to encourage the desired behavior. Regression Analysis can be used with various data sets to derive rule systems or more information for rule development and improvement. For example, the relationship between individual reservoir storage versus total reservoir storage can help to determine which reservoirs are more optimally used for storage and which should be drawn down first under demand.

4.2 Caveats and Future HEC-ResPRM Development

Because limited data was available, and due to limited confirmation of the accuracy of this data, the pilot model does not attempt to perfectly represent the system. Local inflows (Middle Diyala) were neglected, but can easily be added. No other significant physical features of the system were not accounted for in the pilot model, however, the available data deserves thorough review by knowledgeable engineers from the Iraq Ministry of Water Resources. Improved input data will significantly help the model and can change it from a pilot or example model to one with real-life applicability.

Certain phenomena cannot be captured by this model. Short floods, for example are easily missed with the monthly timestep. This fact must be considered when analyzing results. There are ways to examine short-duration floods, such as those that would occur due to rainstorms. The approach would use the statistical analysis to determine the magnitude and frequency of daily peaks that are associated with certain magnitude monthly flows. Then penalties associated with monthly flows can be increased accordingly.

An obstacle encountered in network flow modeling is the problem of non-convexivity. When penalty functions are added to the model that are not concave, the solver cannot ensure a global optimum. The ResPRM solver uses an approach called Restricted Basis Entry to enable it to selectively choose which variables can enter the basis, allowing it to solve non-convex problems. However, a global optimum is not guaranteed. Users can improve the chances of reaching a global optimum by attempting several runs for the same alternative but only changing the starting solution. Another approach is to simplify the system representation to the extent that all penalty functions used are convex. While this is not as accurate, it may at times be more useful to have a model of a simplified system that can be easily run. In optimization modeling there is always a tradeoff between the degree to which a system must be simplified to easily model it, and the loss of accuracy caused by adjustments to the solver in order to solve more complex problems.

ResPRM is a relatively new model and subject to rapid ongoing development. Future versions of the ResPRM software will have several features which were unavailable at the time of this study. Evaporation is not considered in the pilot model, as it is not functional in this version of ResPRM. Routing equations are also not in this version but will be in the future. Other features that will be enabled in the future include the following: metric system units, channel routing, evaporation, and side constraints. It will be good to use future versions in Iraq, particularly when the metric units are enabled.

5 Conclusions

HEC-ResPRM is a reservoir system optimization model developed to assist reservoir operators in improved decision-making by demonstrating the optimal possibilities for reservoir management. The Diyala pilot study was performed in order to demonstrate the potential for using HEC-ResPRM to optimize reservoir operations in Iraq. This report documents the process of developing such a model and can be used as influence to produce new models. The report describes the steps of model development and how to run the model once it has been built in the ResPRM software.

A pilot ResPRM model was produced that includes several different types of demands on a system and shows how these can be modeled. This model can be duplicated, using the step by step guide in Appendix A, or new models can be easily formulated. As a pilot model, the intention is strictly to demonstrate the development process and structure of reasonable penalty curves rather than determine precisely accurate curves. Much of the further model refinement is outside the scope of this pilot project and will be left to the discretion of MoWR. MoWR and others can use the HEC-ResPRM in conjunction with ResSim or alone to improve and analyze reservoir operations. As an optimization model, ResPRM offers an idea of the best outcome that can be expected for the system or any particular operating strategy.

References

Director General of Irrigation. *Discharges for Selected Gaging Stations in Iraq 1959-1975*. Republic of Iraq Ministry of Irrigation. Baghdad, Iraq. August 1976.

Harza Engineering Co. in association with Binnie & Partners. *Hydrologic Survey of Iraq. Final Report, Volumes I, II, & III*. Prepared for the Government of Iraq, Ministry of Agriculture. Baghdad, Iraq. July 1963.

Harza Engineering Co. in association with Binnie, Deacon & Gourley. *Hydrologic Survey of Iraq. Discharges for Selected Gaging Stations in Iraq 1957-1958*. Republic of Iraq Development Board. Baghdad, Iraq. May 1959.

Harza Engineering Co. in association with Binnie, Deacon & Gourley. *Hydrologic Survey of Iraq. Discharges for Selected Gaging Stations in Iraq 1930-1956*. Government of Iraq Development Board. Baghdad, Iraq. May 1958.

Israel, M. S. and J. R. Lund. Priority preserving unit penalties in network flow modeling. Journal of Water Resources Planning and Management. pp, 205-14. Jul/Aug 1999.

USSR V/O Selkhozpromexport. *General Scheme of Water Resources and Land Development in Iraq*. 8 vols. Republic of Iraq Ministry of Irrigation. Moscow-Baghdad, 1982.

US Army Corps of Engineers. (1996). "Developing Seasonal and Long-term Reservoir System Operation Plans using HEC-PRM." RD-40. US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA

U.S. Army Corps of Engineers. North Western Division. *Iraqi Dam Assessments*. Iraq, June 2003.

Appendix A

Step-by-step Guide to HEC-ResPRM Pilot Model

The following outline describes the steps taken to develop Diyala ResPRM Pilot Model. These instructions can be followed in order to duplicate the modeling process and the model itself. In the future, an official Quick Start Guide will be available to take a user through the generic steps of setting up a model in HEC-ResPRM.

1. Create a directory in which to put your PRM projects. This directory will have to be under a minimal number of subdirectories with no spaces, because PRM cannot handle long path names (e.g., ***C:/PRM/projects*** is good whereas ***C:/My Documents/otherstuff/PRM/my prm projects*** is too long and has spaces in the name). Under this directory, create a subdirectory called "***base."*** This is mandatory for creating a project space.

2. Open PRM.

3. Set up the new project.
   Tools -> Options
   a. *Model Directories* Tab:
      Add Location – give it a generic name (you can store more than one project in this directory. Browse to find the directory where your project will be stored. The selected directory selected should have a subdirectory named "**base.**"
   b. *General* Tab:
      Select "Show Confirm on Exit" and "Reload last Watershed at Startup"

4. Select the Watershed Setup in the module dropdown menu near the top right of the screen.
   Module: Watershed Setup

5. Create a new watershed
   File -> New Watershed
   a. Name the watershed "DiyalaPilot_bg." (BG stands for British Gravitational units)
   b. Make a description of the project.
   c. Select British units. (***Future versions will allow SI units, but until that time, users must work with British units***.)
   d. Select a time zone.

6. Allow editing of the watershed.
   Edit -> Allow Editing
   or click on the yellow lock in the upper toolbar.

7. Set up a Watershed Configuration
   The configuration will hold all the elements of a specific part of the project. For this pilot study, there need only be one configuration, whereas larger models

could make use of several different configurations that would hold different subsets of the study area.

Watershed -> Configuration Editor…

Configuration -> New

a. Name the configuration.
b. Make a description of the project.
c. Set the time step to be MONTHLY. Currently ResPRM only works on a monthly time step.
d. Save the Configuration.

8. Set up the background maps and images

   View -> Layers

   a. Edit -> Allow layer editing
   b. Maps -> Add map layer
   c. Add the shape files (*.shp) for rivers, country borders, lakes from the PRM directory.

9. Set up the model to use the desired river system

   Watershed -> Import -> Stream Alignment

   a. Select by NAME and choose only the DIYALA.

10. Note the numbers displayed on the map next to the stream alignment. The highest numbers should be the furthest upstream, but this is not the case. To correct….Select the stream editing tool from the RHS of screen. Select the DIYALA by right clicking on the orange stream alignment and select Reverse Direction.

11. Add Reservoirs and Diversions and Rename Computation Points
    a. From the left-hand toolbar, select the type of element you want to add.
    b. Hold "control" while clicking on the stream alignment where you want to add the element.
    c. Name and describe the element. ***Keep names to ten or fewer characters***, because PRM will store the name using only the first ten characters, and if two elements have the same first ten characters, PRM will not be able to distinguish between the two.

12. Save the Watershed Configuration

    Watershed -> Save Configuration

13. Now that the Watershed Configuration has been set up, begin work on the Network Module.

    Module: Network

14. Set up a new network.

    Network -> New

a. Name your network
b. Create a description of your network
c. Select the Watershed configuration on which this new network will be based. (This tells PRM which elements to import to this network. It will automatically bring in all reservoirs and diversion that exist in the watershed configuration selected.)

15. Add stream segments or reaches that connect the main channel and reservoirs and diversions, starting with the most upstream point. In the case of the Diyala pilot study, the first stream reach will connect the bottom of Derbendi Khan Reservoir with the Middle Diyala irrigation diversion. This is done by selecting the stream reach icon on the left-hand tool bar, then holding “control” which using the mouse to click on the upstream point and then clicking on the downstream node.
16. Add a node at the upstream end of the basin as an inflow point. Name this node “DK Inflow.”

17. Save the network:
    a. *Network -> Save*
    This step saves the network only in the current session of ResPRM.
    b. *File -> Save Watershed*
    This step will save the network in the project, so that it will be saved even if the project is closed.

After the network describing the watershed has been built, penalty functions and constraints must be added to the model.
Notes on penalty curves:
Penalty functions are required by PRM for:
Reservoir Storage
Reservoir Release

Penalty functions are divided into a number of layers. There are **seasonal penalty functions** that allow variation according to month, or a single seasonal penalty function can be assigned to all months. There are also **penalty sets** which can be defined for each interest that might have a penalty. **Composite penalties** exist for each month and are the sum of all penalty sets for that month.

Penalty functions are defined from zero to infinity. PRM extrapolates the outer limits of the penalty function based on the data entered by the user. Because the user typically defines the function at zero, it is on the higher end that the extrapolation always occurs. It is important to be sure that the slope of the penalty function in the last piece is correct.

18. Add inflow data information.
    a. Right-click on the inflow junction at the upstream end of the system.

b. Select *Edit Junction Properties*.
c. *Local Flow* Tab:
   Highlight the first row under "Name" and enter "DK Inflow."
   The factor can be set as one, which assumes no losses.

19. Add penalties and constraints to the reservoirs.
    Edit -> Reservoirs…
    a. BE SURE to select a reservoir from the first dropdown list.
    b. *Storage* tab:
       i. Although this pilot model will not penalize against storage, PRM requires a penalty function for reservoir storage.
       ii. A default composite has been made automatically. Note that it is a flat line, showing zero penalties for level of storage.
    c. *Release* tab:
       i. Make new composite penalty function for flood releases and name the composite "Flood Comp."
          Composite -> New
       ii. Make a new **penalty set** and name the set "Flood."
          PenaltySet -> Rename
       iii. Because the flood penalty will not change over the course of the year, the default "all year" **seasonal penalty set** will be used. Enter the flood penalty function data for this reservoir in the main table in the center of the penalty editor.
    d. *Power Release* tab:
       At the time of writing, this penalty editor has not been enabled to automatically create default penalty sets.
       Create the power release penalties:
       i. PenaltySet -> New
          Name the penalty set "Hydropower." Because there is only one kind of hydropower penalty set, there will be no composite penalty function.
       ii. Next, create seasonal penalty components. Highlight the "hydropower" penalty set.
          Seasonal -> New
          The penalty function will not vary according to month, so name the seasonal penalty "all year."
       iii. Now, because the model is run on a monthly timestep, there will be a new table called Monthly Assignments with dropdown selectors for each month. Select "all year" seasonal penalty for each of drop downs.
       iv. Although there are radio buttons to allow the user to select which type of units to enter penalty function data in and whether to enter the data as slope or penalty, it is best to leave these at their default setting. At this stage in ResPRM software development, this is

important to ensure that there are no conversion errors. Enter the penalty function data.

e. *Constraints* tab:
   i. Select *Storage* in the constraint type dropdown. Enter the storage upper and lower bounds. The upper bound should be the storage associated with the maximum reservoir stage. The lower bound for this pilot study was selected as the minimum level at which hydropower can be generated.
   ii. Select *Releases* in the constraint type dropdown menu. Enter the minimum (zero) and maximum for releases.

f. *Evaporation* tab:
   The evaporation modeling capabilities are still in development. Leave these options alone.

g. *Observed Data* tab:
   *S*elect any locations for which observed data is available and will be compared to model results. This step is not mandatory.

h. *Elevation* tab:
   *E*nter the data for the stage-storage-surface area relationship.

i. Save the changes.
   Reservoir -> Save
   Network -> Save
   File -> Save Watershed

j. Repeat these steps for the other reservoir.

20. Add penalties and constraints to the reaches.
   Edit -> Reaches
   No constraints or penalty functions are needed for any of the release except the outflow reach that connects the Diyala with its junction at the Tigris River. Here a penalty function is needed for the provision of minimum instream flows and to ward against flood level flows.
   a. *Flow* tab:
      i. Select the outflow reach. There is no default composite for reaches, because PRM does not require penalty sets for reaches.
      ii. Add three composite penalty functions, called “Total Comp,” “Flood Comp,” and “Qmin Comp.” This will allow the user to easily make model runs using only flood penalties, only minimum flow penalties, or both.
      iii. Add a penalty set called “Flood.” Highlight this new penalty set and note that a default “all year” seasonal penalty was automatically created, and this seasonal penalty was selected for each month. Add the data for the flood penalty function.
      iv. Repeat step c for minimum flows.
      v. For each composite penalty function, select the desired penalty sets. In other words, for the total composite, check the boxes next to both Flood and Qmin. For the Flood Composite, only check the

box next to Flood. For the Qmin composite, only select the box next to Qmin.

b. *Constraints* tab:
   Add an upper bound and a lower bound (zero).
c. *Observed Data* tab:
   *S*elect any locations for which observed data is available and will be compared to model results. This step is not mandatory.
d. Save the changes.
   Reservoir -> Save
   Network -> Save
   File -> Save Watershed

21. Add penalties and constraints to the diversions.
    Edit -> Diversions
    a. BE SURE to select a diversion from the first dropdown list.
    b. *Flow* tab:
       i. No default composite exists, so create a composite for the irrigation diversion penalties and name it "Irrig Comp."
          Composite -> New
       ii. Create a penalty set called Irrigation.
          PenaltySet -> New
          Select the checkbox next to this new penalty set so that it is part of the irrigation composite.
       iii. Highlight the penalty set. Note that an "all year" default seasonal penalty function has been created. Change the name of this default to "January," because a different irrigation penalty function will be used for each month.
          Seasonal -> Rename
       iv. Create seasonal penalties for all the months.
          Seasonal -> New
          Then select the correct month in each of the dropdown selectors under "monthly assignments."
       v. Add the penalty function data to each of the seasonal penalty functions.
          Although there are radio buttons to allow the user to select which type of units to enter penalty function data in and whether to enter the data as slope or penalty, it is best to leave these at their default setting. This will ensure that there are no conversion errors. Enter the penalty function data.
    c. *Constraints* tab:
       The Constraint Type dropdown says "Flow." Enter the minimum (zero) and maximum for flow through the diversion.
    d. *Observed Data* tab:
       *S*elect any locations for which observed data is available and will be compared to model results. This step is not mandatory.

e. Save the changes.
Reservoir -> Save
Network -> Save
File -> Save Watershed

f. Repeat these steps for the other two diversions.

22. Now that the penalty and constraint data has been entered into the model, alternatives should be created to be used for the model runs.
Alternative -> Edit
23. Give the alternative a name and description and select the network that it is based on (there is only one choice if you only made the one basic network!).
Alternative -> New
This expands the dialogue box.
    a. *Penalty Assignments* tab:
    For each model component, select the appropriate composite penalty. Typically there will be only one choice unless multiple composites exist.
    b. *Reservoir* tab:
    Here, the user can constrain the beginning and ending reservoir storage levels. For the first run, the user may wish to set these constraints at the values for normal operating levels.
    c. *Time-Series* tab:
    This is where input time-series data is entered. Highlight the location of the data then click the "Select DSS path" button at the bottom of the window. This will allow the user to navigate to the appropriate DSS data file and select the correct records. In the case of this pilot model, the user is merely selecting inflow values at the Derbendi Khan reservoir.
    d. *Observed Data* tab:
    If any observed data was selected in this model, this is where the user will enter the DSS file and record for that data.
    e. *Compute Options* tab:
    Since there are nonconvex penalty curves in this model, select "Restricted Basin Entry" towards the bottom of the window.
    f. *Output* tab:
    Don't need to do anything here.
    g. Save the alternative.
    h. Other alternatives can be created in a similar fashion with different composites if multiple runs are desirable for comparative purposes.
    i. Save the changes.
    Reservoir -> Save
    Network -> Save
    File -> Save Watershed
    j. If another alternative is desired, repeat the above steps. The main differences between alternatives may be the choice of which composites are applied in each of the alternatives.

24. Now that the Network has been set up, begin work on the Optimization Module. This is the module where model runs are set up and made.
    Module: Optimization

25. Create a new optimization.
    Optimization -> New
    a. The default name for this run will be the date it was created. CHANGE the name to something meaningful, or things will get very confusing as the user makes new optimizations. And DESCRIBE it!
    b. Change the Start and End Dates to reflect the period of record for input data or use a different dates to model a shorter window of time. Keep in mind that the dates entered here will be translated by one month due to errors in the way the model interacts with DSS.
    c. Select the Alternatives that to be modeled in this optimization.
    d. To run the optimization for the first time, right-click on the desired alternative and set as active. Then press the compute button.
    e. Subsequent computes may require that the user holds down the control key. If the model does not register that a change has been made, this must be done to force a compute.
26. After running the model, the results can be viewed through a variety of different approaches, but data is primarily viewed in DSS.
    a. Open the results file in DSS.
    b. Right Clicking on elements in the ResPRM interface will allow the user to view time series graphs of the results at the selected locations.

Appendix B

Prioritization with Non-economic Penalties

The determination of penalty curves that reflect a specific prioritization is an optimization problem in itself (Israel and Lund, 1999). The approach taken to ensure that penalty curves will support the correct prioritization of variables in the optimization was to consider each of the separate interests and write equations that would ensure that the unit penalty was greater for higher priority interests. By considering the placement of an interest relative to others in the system, one can determine which interests are in conflict and which compete for the same unit of water. One can also determine which interests compete cumulatively, such as those in series that have flow-through demands. The following describes each interest in order of priority and the determination of which other interests are in competition for the same water, as well as how to assign penalty functions that assign proper weights. Variables in this section are named in accordance with the labels in Figure 1.

1. Avoid extreme high releases.

priority = unit penalties: $\boldsymbol{f_{A3}, f_{C3}, f_{F3}}$

For flood control, unit penalties will be positive because penalty increases with increasing flow. The penalty incurred for releasing high flows must be greater than the reduction of penalty incurred by meeting other/downstream objectives. So, unit penalty must be greater than the negative unit penalty from any other flow path.

Releases from Derbendi Khan Reservoir (A):

There is a unit penalty of zero on hydropower at flood level releases, therefore hydropower at Derbendi Khan is not a conflicting interest.

prospective flow path: A → B $f_{A3} > -d_{B2}$

Unit penalty for high releases at A must be greater than the greatest reduction of penalty incurred by releases flowing to B to meet irrigation demands.

A → C → D/E $f_{A3} > -\min(hp_C) - d_{D/E2}$

Unit penalty for high releases at Derbendi Khan (A) must be greater than the sum of the reduction of penalty incurred by release through hydropower at A and C and downstream irrigation at either D or E.

Again, hydropower does not compete with flood (these penalties are not incurred at the same flow regimes), whatever.

A → C → F $f_{A3} > -\min(hp_C) - q_{F1}$

Unit penalty for high releases from A must be greater than the negative sum of the value of the decreasing unit penalties incurred through generation of hydropower and irrigation diversion.

Releases from Hemrin Reservoir (C):

A → B

There are no competing interests for water that takes this route, because hydropower generating flows at Derbendi Khan (A) are smaller than flood level flows at Hemrin (C).

A → C → D/E $f_{C3} > -d_{D/E2}$

Unit penalty on high releases from Hemrin (C) must be larger than the reduction of penalty due to flows to either of the downstream irrigation diversions, CHR or Al Khalis (D/E).

A → C → F $f_{C3} > -d_{F2}$

For flows in the range of high releases, negative penalty cost associated with upstream releases (hydropower at Derbendi Khan and Hemrin), must be less than flood penalties. As high flood penalties are not incurred until reaching extreme flows, this is not an issue. Hydropower is already maxed out at these levels and instream flow demands are also maxed out, making unit penalties = 0 for all +– potentially competing interests.

Downstream channel releases (F):

A → B
A → C → D/E

For these routes, there are no competing penalties because hydropower generating flows are lower than those that incur a flood penalty. Irrigation diversions do not compete with the restriction of flood flows.

A → C → F

The only competing objective is hydropower generation, so if the regime for generating hydropower is larger or as large as the regime for producing flooding, then there is competition, however, this is not the case.

2. Provide Instream Minimum Flows to Tigris

priority = unit penalties: $\boldsymbol{q_{F1}}$

For minimum instream flow requirements, the reduction of penalty incurred for releasing maintenance flows must be greater than the reduction of penalty incurred by sending those flow units to other system demands. Competing demands are primarily irrigation. It also must be greater than the cost incurred should those flows be in the low flood regime. So, the negative unit penalty on minimum flows must be greater than the negative unit penalty from any other flow path.

A → B $-q_{F1} > -d_{B2}$

The reduction in penalty incurred by meeting instream flow demands must be greater than the reduction in penalty incurred by diverting that unit of water to irrigation at B instead.

A → C → D/E $-q_{F1} > -d_{E/D2}$

minimum flood unit penalties are 0. the minimum irrigation diversion penalty is d_2. Hydropower would be incurred regardless of which path the water were to take and is not a competing demand, as return flow is 100%. Flood prevention is a competing interest.

$$-q_{F1} > f_{A2} + f_{C2}$$

3. Provide 90% Irrigation Demand

priority = unit penalties: $\boldsymbol{d_{B2}, d_{D2}, d_{E2}}$

Unit cost associated with the piece between 20%-90% must be beat.

It is assumed that the unit penalties will be equal for all three irrigation demands. This means that under ordinary flow conditions (no flooding), Mushtarak and Al Khalis demands will be filled first, as routing water this way incurs a decrease in penalty both for the irrigation itself and for the hydropower generated as water is routed through the Hemrin reservoir. At flows greater than the maximum needed to generate at least 80% of the hydropower capacity, demand at all three irrigation districts will be equal and the model with arbitrarily send water to one until it reaches 90% of demand and so on.

Irrigation at the Middle Diyala Diversion (B):

A → B $-d_{B2} > f_{A2}$

Diversions to this irrigation district may conflict with restrictions on flood releases at Derbendi Khan. High

A → C → F $-d_{B2} > -\min(hp_{C2}) - q_{F2}$

Irrigation at the Mushtarak (CHR) or Al Khalis Diversion (D/E):

A → B $-d_{D2} = f_{B2}$

A → C → D/E $-d_{D2} > f_{A2} + f_{C2}$

A → C → D/E $-d_{D2} > -q_{F2}$

4. Provide Hydropower at 80% of Capacity

priority = unit penalties: $\boldsymbol{hp_{A,min}}$, $\boldsymbol{f_{C,min}}$

Because there are no competing interests for hydropower generation, there are no constraints on unit penalties. Flood penalties at each of the reservoirs is at a much higher level than the flood demands. Probably even if db is maximized I don't know!!

5. Avoid Moderately High Flood Releases

priority = unit penalties: $\boldsymbol{f_{A2}}$, $\boldsymbol{f_{C2}}$, $\boldsymbol{f_{F2}}$

Releases from Derbendi Khan Reservoir (A):

A → B $f_{A2} > -d_{B3}$

A → C → D/E $f_{A2} > -d_{D3}$

A → C → F $f_{A2} > -d_{F3}$

Releases from Hemrin Reservoir (C):

A → B none!

A → C → D/E $f_{C2} > -d_{D3}$

A → C → F $f_{C2} > -d_{F3}$

6. Supply 100% Irrigation Demand

priority = unit penalties: $\boldsymbol{d_{B3}}$, $\boldsymbol{d_{D3}}$, $\boldsymbol{d_{E3}}$

Irrigation at the Middle Diyala Diversion (B):

A → B none

A → C → F $-d_{B3} > -q_{F2}$

Irrigation at the Mushtarak (CHR) or Al Khalis Diversion (D/E):

A → B $-d_{D/E3} = -d_{B3}$

A → C → D/E $-d_{D/E3} > -q_{F2}$

7. Maintain greater than minimum instream flows

priority = unit penalties: $\boldsymbol{q_{F2}}$

As the lowest priority interest, there are no comparative constraints in formulating minimum instream flow unit penalties.